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COMPARISON OF THE PERFORMANCE OF AN EMBANKMENT DAM AND CONCRETE GRAVITY DAM UNDER NEAR-FIELD EARTHQUAKE

Asmidar Mohamad[1], Nik Zainab Nik Azizan[2*], Muhammad Ashraaf Ibrahim[3], Shamilah Anudai @ Anuar[4], Nor Faizah Bawadi[5], Tahara Ramadzan Md Kassim[6]

[1] Faculty of Civil Engineering & Technology, Universiti Malaysia Perlis, Malaysia
Email: asmidar.mohamad@studentmail.unimap.edu.my
[2] Faculty of Civil Engineering & Technology, Universiti Malaysia Perlis, Malaysia
Email: nikzainab@unimap.edu.my
[3] Faculty of Civil Engineering & Technology, Universiti Malaysia Perlis, Malaysia
Email: s191200485@studentmail.unimap.edu.my
[4] Faculty of Civil Engineering & Technology, Universiti Malaysia Perlis, Malaysia
Email: shamilah@unimap.edu.my
[5] Faculty of Civil Engineering & Technology, Universiti Malaysia Perlis, Malaysia
Email: norfaizah@unimap.edu.my
[6] Kulliyah of Engineering, International Islamic University Malaysia, 53100 Selangor, Malaysia
Email: tahara11@gmail.com
[*] Corresponding Author

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Abstract:

One of the crucial elements impacting the dam's seismic behaviour is the height of the reservoir's water. As such, this study employs Incremental Dynamic Analysis (IDA) to examine the performance of the Semenyih earth embankment dam and concrete gravity dam during near-field earthquakes with variations in the water level behind the embankment dam. Water levels varying from 0 to 1/3, 1/2, 2/3 and the entire height of the embankment dam are considered an essential measure of how well the structures perform. These assessments were conducted under seven near-field earthquake datasets utilising the ABAQUS finite element framework. Seven ground movements were transformed into response spectra and adjusted by the soil type's characteristics to create an elastic response spectrum. According to Eurocode 8, the soil type A-based elastic response spectrum was created. The limit states of the embankment dam that are yielding and the final condition are discovered by applying the IDA approach based on static analysis. The earth embankment dam results of average Peak Ground Acceleration (PGA) is 0.02 g for the yielding state and 0.57 g and 0.52 g, respectively, for the ultimate state. Meanwhile, the concrete gravity dam reveals 0.46 g and 0.59 at the yielding

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point, and the ultimate state is 0.59 g and 0.69 g. According to the findings, both types of dam operation at zero water level pose a greater danger than a full water reservoir, and the displacement for both dams was larger as the PGA rose. Lastly, the comparison between these two suggests that concrete gravity dams are more reliable to withstand the effect of seismic load.

Keywords:

Embankment Dam, Concrete Gravity Dam, IDA Analysis, Seismic Load

Introduction

Dams are massive structures used for various purposes, such as water resources, irrigation, power generation, flood control and recreation. Dams have significantly contributed to humanity's development as early buildings in civil engineering (Gordan et al., 2021). However, most dams are located in seismic zones. Due to the earthquake, the affected dam poses a significant risk of damage or failure, leading to loss of life and property damage. There were two types of dams: concrete dams and embankment dams. Both dams are the most common designs due to their design consideration and characteristics (Flores-Berrones & Patricia López-Acosta, 2020). As such, the embankment dam is built using its natural rock fill or earth fill. Meanwhile, the concrete gravity dam was constructed with concrete that can withstand the forces of its weight (Chopra, 2020; Zeidan, 2014). Even concrete dams perform better than embankment dams due to seismic effects. However, they are still vulnerable to this mother nature (He et al., 2019). In the past, dams failed to engage in seismic activity, such as the Shih Kang Dam in Taiwan, which was affected by the Chi-Chi earthquake in 1999, the Koyna Dam in India in 1967 by the Koyna earthquake, and a few more (Tidke & Adhikary, 2021). Hence, numerous studies have been conducted to investigate how concrete dams behave under seismic loads (Aldemir et al., 2013; Chen et al., 2019; Sarkhel et al., 2021). Notably, most research used the nonlinear evaluation method to assess the seismic response on the dam.

Embankment dams are one of the most commonly used in countries worldwide since they require no additional equipment to construct, only what is readily available and very usable earth fill. They were built on distinct varieties of subsoils like alluvial deposits and permeable land. This versatility makes them ideal in most locations. Nonetheless, embankment dam failure has been disastrous in history, causing loss of life and property (He et al., 2019). In particular, strong ground motion resulted in a weak foundation and unstable embankment. Thus, this gains more attention from other researchers to study the performance of embankment dams under earthquake event(Chowdhury et al., 2020; L. Mejia & Dawson, 2019; L. H. Mejia et al., 2022)

Peninsular Malaysia was not seismically active. However, it is still vulnerable to seismic hazards and unable to resist the earthquake effect. Moreover, Malaysia is situated near the Pacific Ring of Fire and is not safe from earthquake strikes even though Malaysia is not in the Ring of Fire (Sulaiman* et al., 2019). Malaysia experienced an earthquake in Ranau, Sabah, on 5 June 2015, recorded with 6.2 magnitudes (Astro Awani, 2015). The impact resulted in 18 people being killed and physical damage to infrastructures. Some public and private buildings near Ranau and Kundasang areas, including schools, hospitals, mosques, temples, and a water tank, were also affected slightly. In addition to that, buildings located at the top of Mount Kinabalu were knocked down by rockfalls and landslides (Indan et al., 2018). Another example

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is the Liyutan embankment dam after the Chi-Chi earthquake, with a magnitude of 7.3 in Taiwan in 1999, which caused minor opening and closing of a few expansion joints in the crest sidewalks. A transverse fracture, which followed the crest road to the left of the left abutment, was one of a few significant fractures (Charlwood et al., 2000).

This paper focuses on the performance of both dams under seismic load at varying water levels from full to empty dam using the Incremental Dynamic Analysis (IDA). The parameters varied, including two types of dams with 50 m height, ground motions input, material properties of the dam, and loading: self-weight, hydrostatic pressure, and seismic load. Lastly, it includes various water levels (full, 2/3, half, 1/3 and zero). The existence of water in the reservoir influences the response of the dam under an earthquake strike. On the other hand, (Gorai & Maity, 2022; Linda & Kadid, 2022) investigated the dam's performance under seismic load using the dam reservoir foundation interaction analysis with empty and full water levels.

The ground motion selection is an essential step in the assessment and design processes. In IDA, the structure is subjected to a sequence of earthquake recordings that increase in intensity, pushing the structure to its harsher limit states. Thus, by applying a series of earthquake records to a structure at progressively higher intensity levels, a computer can perform time-consuming analysis methods like IDA. This causes the structure to change from an elastic state to an inelastic state and ultimately collapse. Furthermore, this makes it possible to identify a structure's capacity and limit states.

Materials and Methods

Numerical Modelling

The performance of an embankment dam with varying water levels will be studied by performing an IDA. This study utilises the 2D Planar in ABAQUS software to model the embankment and concrete gravity dam. Both dams were subjected to various water levels, including full, 2/3, half, 1/3, and 0 m of dam height. Consequently, the dam was analysed according to its self-weight, hydrostatic pressure on the upstream wall and earthquake loading at the base. The total dimensions of the Semenyih embankment dam and concrete gravity dam are illustrated in Figures 1 and 2. The material properties for this model are tabulated in Table 1.

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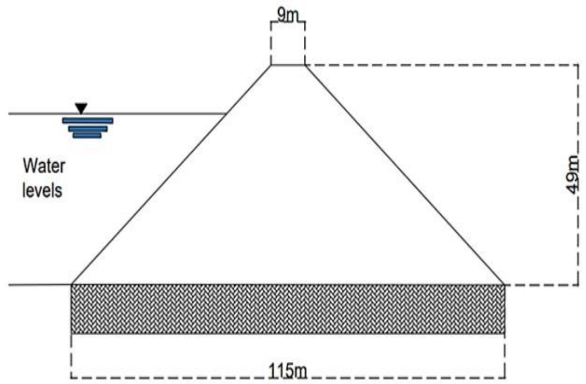

Figure 1: Dimension of Semenyih Embankment Dam

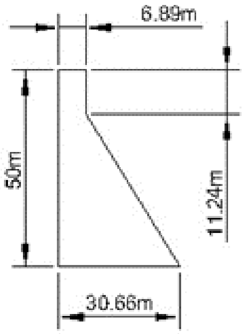

Figure 2: Dimension of 50 M Concrete Gravity Dam

Table 1: Material Properties of Dams

	Earth embankment dam core	**Shell**	**Concrete gravity dam**
Dry density	1740 kg/m³	2050 kg/m³	2643 kg/m3
Young's Modulus	35 MPa	102 MPa	31513 Mpa
Poisson's Ratio	0.35	0.25	0.2
Permeability	1×10^{-9} m/s	1×10^{-6} m/s	

A total seven number of ground motions were selected and summarised in Table 2. The ground motions were obtained from the Pacific Earthquake Engineering Research (PEER) strong motion database. The motion data must fulfil the criteria such as near field distance, R is less than 15 km from the earthquake source with a magnitude greater than 5.5 Mw and Peak Ground Acceleration (PGA) is equal to or greater than 0.15 g. This allows the effect of different ground motion characteristics to be investigated at different scaled levels.

Table 2: Summary Parameters of Ground Motions

No	**Earthquake Name**	**Date**	**Magnitude (M)**	**PGA-H (g)**	**PGA-V (g)**
1	San Fernando	9 February, 1971	6.61	0.382	0.194
2	Irpina Italy	23 November, 1980	6.90	0.32	0.240
3	Friuli Italy	6 May, 1976	6.50	0.357	0.277
4	Westmorland	26 April, 1981	5.90	0.194	0.232
5	Imperial Valley	15 October, 1979	6.53	0.277	0.194
6	Mammoth Lakes	25 May, 1980	6.06	0.324	0.250
7	Norcia Italy	19 September, 1979	5.90	0.208	0.176

Incremental Dynamic Analysis (IDA)

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The IDA method was employed to analyse the structure performance under seismic capacity (Vamvatsikos & Allin Cornell, 2002). The goal of IDA is to determine the full range of a structure's performance, from elastic to yielding, nonlinear inelastic, and ultimately leading to global instability. This is achieved by applying a series of nonlinear time history analyses to a structure for numerous ground motion records and scaling each record to different intensity levels [9], [20].

To perform the analysis, a scaling of ground motion Intensity Measure (IM) and embankment Dam Measure (DM) is necessary to develop the IDA curve. PGA serves as the IM in this study, while the displacement of the embankment dam serves as the DM. The scaling technique made use of the structure's basic period spectrum acceleration. First, the analysis in ABAQUS is used to determine the embankment dam's natural frequency, and then 1/f may be used to obtain the fundamental period, T_1. According to Eurocode 8(British Standards Institution. et al., 2005) and Draft Malaysia Standard (Malaysia National Annex to MS EN Eurocode 8:, 2017), the scaling of the response spectrum for the ground motion is based on the first mode of the fundamental period. Subsequently, seven ground movements' time histories were transformed into acceleration response spectra using the SeismoSignal software. This is considering an acceleration of between 0.05 and 1.10 g.

Results and Discussion

Static Analysis

A static analysis of the dam was conducted without earthquake loading in ABAQUS to observe the performance of the embankment dam under its self-weight and hydrostatic loading. The max displacement of the dam was determined for every dam with different water levels, as displayed in Figures 3 (a) and (b).

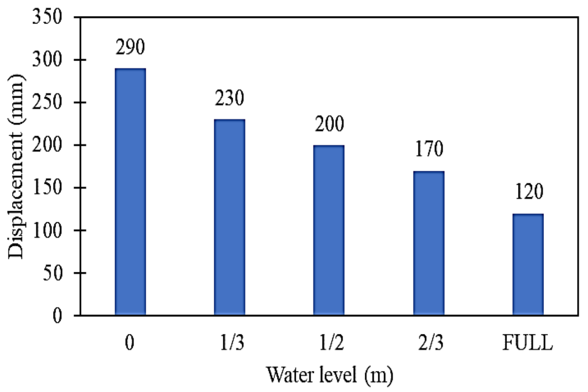

Figure 3: (a) Static Analysis of Embankment Dam

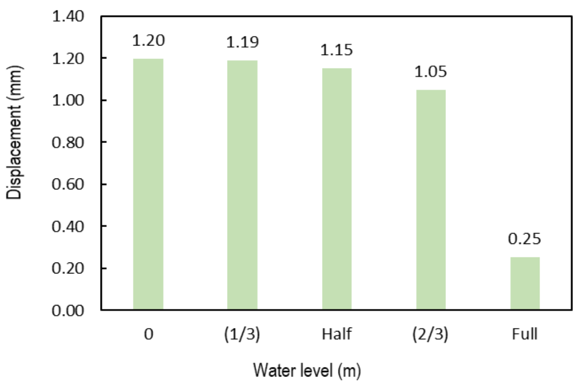

Figure 3: (b) Static Analysis of Concrete Gravity Dam

The results reveal that at full water level, the max displacement is 120 mm, smaller than 290 mm at zero water level for the embankment dam. The same pattern can be observed at the concrete gravity dam as displacement was only 0.25 mm but 1.20 mm at zero water level. As for other water levels less than 2/3 of the dam height, the displacement keeps increasing. This finding explained that the presence of water in the dam has reduced the dam's displacement,

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leading to the settlement of the dam. This is attributable to the water helping the dam to absorb the energy loading like its self-weight (Belmihoub et al., 2022). Notably, the empty dam has the biggest displacement compared to other dams with different water levels. In comparing these two dams, concrete gravity dams are massive monolithic structures that use their weight and stability to resist high water pressure. The embankment dam is unlikely to be stable at low water levels (Norouzi et al., 2020).

Limit State

The mean and median IDA curves are good for evaluating the structural capacity and limit state. Every ground motion was plotted for every water level and ground motion and then was calculated to obtain the mean and the median as illustrated in Figures 4 (a) and (b) until Figures 5 (a) and (b). The dam limit state dam was observed based on the static analysis. As such, the embankment dam with a full water level is considered a yielding state, while the empty dam is considered an ultimate state due to the large magnitude of displacement that can significantly impact the dam and lead to the collapse of the dam. The concrete gravity dam at maximum crest displacement with full water level is lesser than the lower water level.

The mean PGA for an embankment dam with full water suggests that at yielding state until it reaches the ultimate state, the range is 0.05 g > PGA < 0.90 g and decreases to 0.01 g > PGA < 0.54 g at half water level. The PGA decreases as the dam reaches zero water with 0.01 g < PGA > 0.30. The same data implies the median curve.

On the other hand, the mean PGA for a concrete dam with full water was 0.35 g < PGA > 0.60 g at yielding to the ultimate state. At half water level, the result indicates 0.45 g < PGA > 0.55 g. Finally, at zero water, the PGA was 0.50 g < PGA > 0.60 g. The median curve illustrates a bigger PGA when it reaches its ultimate state at all water levels.

According to the IDA curve, dams with zero water level have the greatest displacement compared to dams with water. In this situation, water absorbs the energy loading from seismic occurrences, allowing the dam to last longer. The study from [18] and [25] indicated that the interaction effect between the dams has a great impact on the prediction of the dynamic response of dams. Aside from that, the dam's performance may be observed from the limit state. Furthermore, a concrete gravity dam is more sustainable compared to an embankment dam in terms of crack displacement, with a yielding state of 23.17 mm and an ultimate state of 34.48 mm when posed by the seismic load. Table 3 listed the average PGA for yielding and ultimate state of dams at five different water levels. Moreover, the mean and median of PGA for both dams indicate that an embankment dam has a smaller PGA than a concrete gravity dam. At 0.02 g, the embankment dam starts to reach its first crack, while the concrete gravity dam at 0.46 g.

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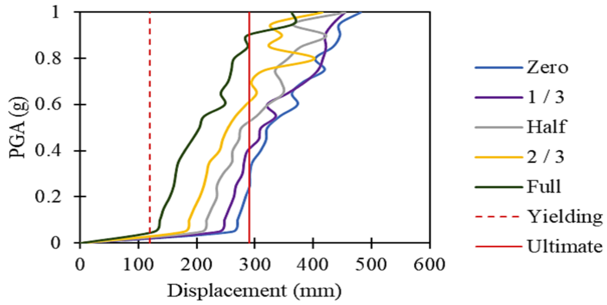

Figure 4 (a): IDA Curve Of Mean for Earth Embankment Dam with Different Water Levels

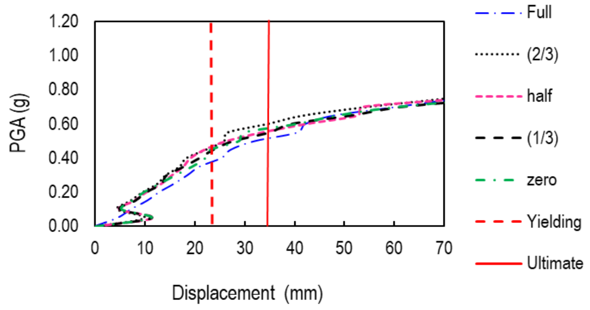

Figure 4 (b): IDA Curve Of Mean For Concrete Gravity Dam with Different Water Levels

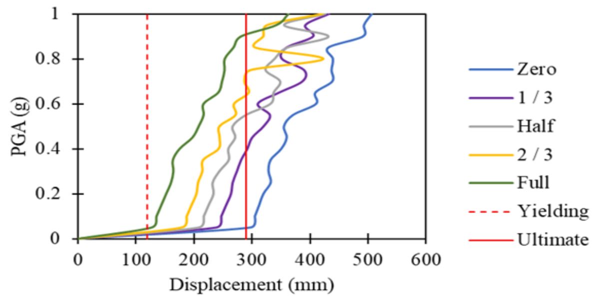

Figure 5 (a): IDA Curve Of The Median For Earth Embankment Dam With Different Water Levels

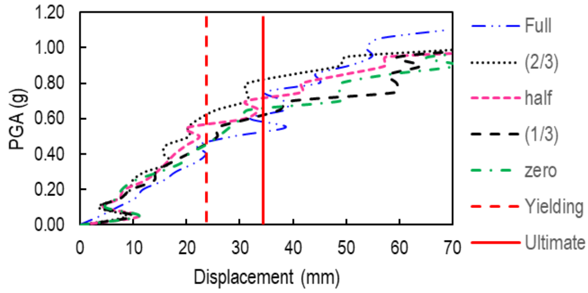

Figure 5 (b): IDA Curve Of The Median For Concrete Gravity Dam With Different Water Levels

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Table 3: Average PGA For Yielding And Ultimate State For Mean And Median

Water levels	Embankment dam				Concrete gravity dam			
	Mean		Median		Mean		Median	
	PGA (g)		PGA (g)		PGA (g)		PGA (g)	
	Yielding	Ultimate	Yielding	Ultimate	Yielding	Ultimate	Yielding	Ultimate
Zero	0.01	0.30	0.01	0.30	0.50	0.60	0.50	0.70
1/3	0.01	0.41	0.01	0.41	0.45	0.60	0.45	0.65
Half	0.01	0.54	0.01	0.54	0.45	0.55	0.46	0.60
2/3	0.02	0.70	0.02	0.70	0.45	0.60	0.55	0.70
Full	0.05	0.90	0.05	0.90	0.35	0.60	0.35	0.80
Average	0.02	0.57	0.02	0.57	0.46	0.59	0.49	0.69

Conclusions

The IDA results reveal substantial insights into the comparative performance of embankment dams and concrete gravity dams subjected to seismic loads. In particular, the concrete gravity dam demonstrates greater earthquake resilience compared to the embankment dam. This is due to the strength and stiffness to resist the internal lateral forces generated by seismic ground motions.

Furthermore, the presence of water prevents the dams from crumbling since the water absorbs seismic energy. According to IDA research, a rise in the PGA results in larger displacement for both dams. This study underlines the significance of PGA in displacement response. Accordingly, concrete gravity dams have greater foundation interaction, reducing the dynamic response of the structure that causes cracking and excessive water seepage. Nevertheless, embankment dams are more vulnerable to landslides, settlement and erosion during the earthquake strike. This comparative study of these two dam types is a critical issue that needs further investigation.

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